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Management and development of Mining Waste from the Dry Process of the Djebel Onk Phosphate Ore Beneficiation Plant (Somiphos) – Tébessa

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Abstract

Phosphate mining at Djebel Onk (Tébessa, Algeria) generates large volumes of solid waste that occupy land, release dust, and contaminate surrounding environments. This study aims to characterize and valorise two types of dry tailings, namely +15 mm screening rejects and fines from pneumatic separation (TSV), in order to reduce their environmental impact and recover residual phosphate. Samples were analyzed using particle size distribution, atomic absorption spectrometry (AAS), X-ray diffraction (XRD), and scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM/EDS). Treatment tests included calcination (laboratory furnace, 700–1000 °C, 15–30 min) and direct flotation (Denver-type cell, with oleic acid and phosphoric acid as reagents). The results show that the +15 mm rejects and TSV fines contain 21.42 % and 23 % P_2O_5, respectively, while the richest fraction (-0.5 + 0.25 mm) reaches 28.99 % P_2O_5 with 1.01 % MgO. Calcination at 1000 °C for 30 minutes produced concentrates with 33.51 % P_2O_5 and near-complete CO_2 removal, whereas direct flotation yielded concentrates of approximately 30 % P_2O_5 with MgO less than 1 %. The novelty of this work lies in the combined application of calcination and flotation, which demonstrates their complementarity for efficient recovery of phosphate from dry tailings. These results confirm the potential for phosphate valorization while reducing environmental impacts and supporting more sustainable mining practices.

1. Introduction

Phosphorus, exploited in the form of phosphate, is an essential element used in agriculture, the chemical industry, nuclear energy, detergent production, and the agri-food sector [15, 10].

The Djebel Onk deposit, located in eastern Algeria, represents the country's main reserve, with resources estimated at more than two billion tonnes. Its industrial exploitation began in the late

Its industrial exploitation began in the late twentieth century with the establishment of the Society Phosphates Mine (SOMIPHOS). This company plays a central role in the Algerian mining sector and contributes significantly to the national economy, with a production of 1.6 million tones in 2018, placing Algeria among the world's leading phosphate exporters [15, 7].

The open-pit exploitation of the deposit is followed by preparation and beneficiation processes designed to produce concentrates that meet international market standards [15, 11]. However, these operations generate large volumes of solid tailings [15, 8], which accumulate over

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extensive areas and represent a major environmental burden.

Despite the strategic importance of Djebel Onk, few studies have focused specifically on the valorization of dry tailings resulting from screening and pneumatic separation processes. The existing literature mainly describes the general composition of Algerian phosphates and their transformation routes but provides limited experimental assessment of combined treatment methods, such as calcination and flotation, applied directly to Djebel Onk tailings.

This study seeks to address this research gap by characterizing and testing the valorization of two categories of dry tailings (+15 mm rejects and TSV fines). The objective is to propose technically viable and economically realistic solutions to recover residual phosphate, mitigate environmental impacts, and promote more sustainable mining practices.

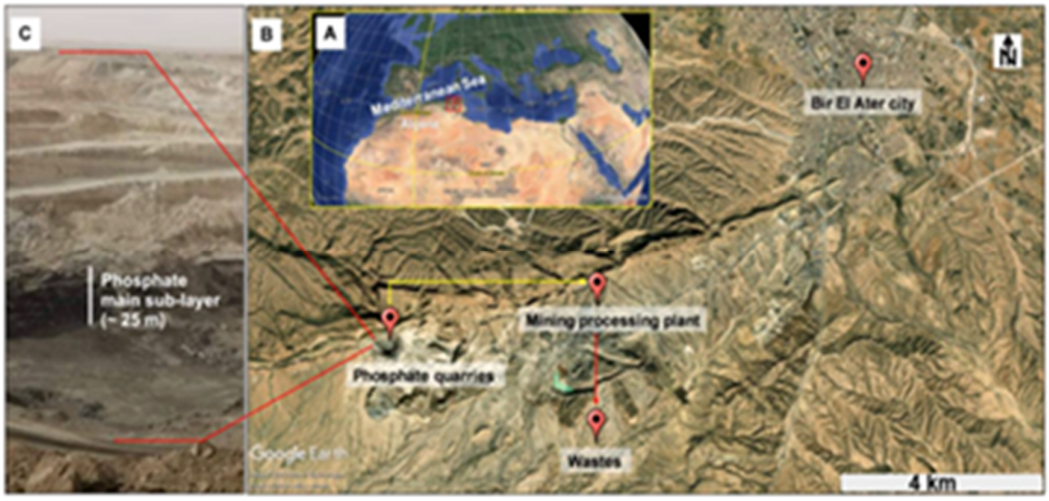


Figure 1. Location of the phosphate deposit studied (Kef Essenoun) and the waste areas (A, B), with a close-up photo of the mined phosphate layer (C) [4]

2. Methodology

2.1. Geographic

Algeria possesses substantial phosphate reserves, estimated at approximately 2.1 billion tons, with an annual mining output of around 1.2 million tons [1]. This study focuses on the Djebel Onk mining complex, located in Tébessa Province in eastern Algeria [13, 16]. Djebel Onk is the country's primary phosphate production site, characterized by large reserves and intensive industrial activity, which generates significant volumes of solid waste.

These wastes are mainly composed of dolomite, calcite, fluorapatite, and kaolinite, and contain elevated concentrations of toxic heavy metals, including uranium, cadmium, zinc, copper, arsenic, and lead. Wind and runoff contribute to their dispersion, potentially contaminating soils and groundwater up to 30 km from the site [13]. Fine particles, particularly slurries, exhibit higher concentrations of these elements, amplifying environmental and health risks. The persistence and mobility of these contaminants represent a threat to local communities, ecosystems, and livestock [2].

This work investigates the performance of two beneficiation methods calcination and direct flotation to increase P_2O_5 content, enhance resource efficiency, minimize waste-related impacts, and support a more sustainable exploitation of Algeria's phosphate reserves.

3. Sample Collection

Two types of waste were sampled at the Djebel Onk beneficiation plant:

- +15 mm screening rejects
- Fines from the TSV pneumatic separation unit

Sampling was carried out over two days. For each discharge, two representative samples, each weighing 30 kg, were collected, with a 30-minute interval between collections.

The sample mass of 30 kg was selected to ensure the statistical representativeness of the discharges while respecting the practical constraints of preparation and analysis. According to mining industry standards, volumes greater than 25 kg are generally required to reflect the

granulometric and mineralogical variability of discharges from industrial processes [13, 16]. This choice also provided a sufficient quantity to conduct all the granulometric, chemical (AAS), mineralogical (XRD), and morphological (SEM/EDS) analyses, as well as the treatment tests (calcination and flotation), while guaranteeing the reproducibility of the results.

4. Sample Preparation

The samples were crushed, homogenized, and quartered. The particle -size distribution was determined by sieving (using a RETSCH AS200 basic vibrating sieve shaker (serial number 22 2504 017 G, 230 V, 50 Hz, made in Germany), and the fine samples were ground in an RM200 mortar mill for chemical and mineralogical analyses.

5. Granulo-chemical and mineralogical characterization

Chemical analysis

• P_2O_5 determined using an automatic Technico 3 (AA) analyzer.

CO_2 measured by the Bernard method.

• Metallic elements Cd, Pb, Zn, and Cu analyzed by atomic absorption spectrometry (AAS).

Mineralogical analysis

• X-ray diffraction XRD performed using a PANalytical X'Pert PRO diffractometer.

Cu Kα radiation, 45 kV, 35 mA.

Scanning speed 0.04°/s.

• Scanning electron microscopy SEM/EDS used to examine particle morphology, surface texture, and elemental composition [5].

This analysis was carried out using a QUANTA 250 microscope manufactured in the United States.

6. Treatment Procedures

6.1. Calcination

Samples of +15 mm rejects, the fraction (-0.5 + 0.25 mm), and TSV fines were subjected to heat treatment in a Gero Carbolite muffle furnace (model AAF 1100, 220–230 V, 50/60 Hz, maximum temperature: 1100 °C) (Figure 2).

Temperatures: 700 °C, 850 °C, and 1000 °C

Durations: 15 and 30 minutes

In the calcination tests, the temperatures used (700, 850, and 1000 °C) and exposure times (15 and 30 minutes) were selected to optimize the decarbonation process,based on previous work on carbonate-phosphate waste and validated by preliminary tests. Several studies have shown that the decarbonation of calcite and dolomite begins around 700-°C and becomes almost complete above 900-°C [2,13,16]. The choice of 1000-°C ensures optimal decomposition of the carbonates, promoting an increase in P_2O_5 content while reducing losses of useful elements.

Regarding the calcination time, durations of 15 and 30 minutes were chosen to compare the effects of a short and extended treatment. These values correspond to the ranges commonly used in the literature to evaluate the energy efficiency and decarbonation kinetics of phosphate releases [1, 5].

The objective was to decarbonate the samples by decomposing the $CaCO_3$ and $MgCO_3$ into oxides, thus enriching p_2O_5.

Figure 2. Carbolite Gero brand muffle furnace

6.2. Direct Flotation

Floatation tests were conducted in a Denver-type flotation cell at the LAVAMINE laboratory (Figure03) under the following conditions:

- Pulp density: 30% solids, 70% water

- PH: 9, adjusted with NaOH

- Stirring speed: 1250 rpm

- Conditioning time: 20 minutes

Reagents used:

- Phosphoric acid (depressant): 2000 g/t

- Oleic acid (collector): 2500 g/t
- Ethanol (activator): 800 g/t
- Pine oil (frother): 1000 g/t

In the flotation tests, the choice of operational parameters (pH, reagents, concentration, and conditioning time) was based on both previous studies and preliminary tests. PH 9 was chosen because it corresponds to the optimal efficiency range of oleic acid-based collectors for carbonate phosphate ores, promoting selectivity towards gangue minerals [1, 13, 16]. Furthermore, several studies have shown that moderate alkaline conditions (pH 8–9) provide a better compromise between P_2O_5 recovery and carbonate impurity reduction [2, 5].

The concentrations of the reagents (oleic acid and phosphoric acid) were set based on the ranges recommended in the literature and then optimized experimentally to obtain concentrates with P_2O_5 > 28% and MgO < 1%. Conditioning time and flotation time were also adjusted according to standard protocols applied to phosphate ores [13, 16]. The objective was to reduce the carbonate and clay content and produce a phosphate concentrate that met industrial specifications.

Figure 3. Denver type flotation cell

7. Results and Discussions

7.1. Chemical Composition of Wastes

Chemical analyses of phosphate ore waste provide essential information for assessing their composition and considering recovery strategies. The results obtained from the chemical analyses of 15mm and fine TSV waste are presented in Table 1.

Table 1. Result of Chemical Analyses for +15mm and Fine TSV Waste

Samples	%P2O5	%CO2	%MgO	%CaO
Rejects +15mm	21.42	12.38	2.84	34.65
Fines TSV	23	11.30	3.20	38

The discharges of phosphates with particle sizes of +15mm and fine TSV contain a P_2O_5 content of 21.42% and 23%, respectively. These contents indicate that both types of discharges still contain a significant amount of phosphate. According to a study on the discharges of Djebel Onk, which generally contain around 20–21% of P_2O_5, [13] this level is considered economically advantageous for possible recovery.

However, the presence of carbonates and cadmium makes it difficult to recycle the material without taking necessary precautions. Techniques such as calcination and flotation are possible, which dissociate carbonates from phosphates. Recycling these wastes could be considered, taking into account the environmental risks associated with heavy metals such as Cadmium.

7.2. Granulo-chemical Analysis of Wastes

The particle size analysis shows that the (-0.5+ 0.25 mm) fraction presents the best quality. It has the highest P_2O_5 content (28.99%) and the lowest CO_2 (6.86%) and MgO (1.01%) contents.

The minimum P_2O_5 content of the run-of-mine is 25% [9].

The results show that a wide particle size range meets the quality requirements, particularly the (-0.5 + 0.25 mm) and (-0.25 + 0.125 mm) fractions, which represent a cumulative weight yield of 37.17%. The + 15 mm rejects have a P_2O_5 content of 21.42%, comparable to that of the run-of-mine, and should therefore be recycled into the

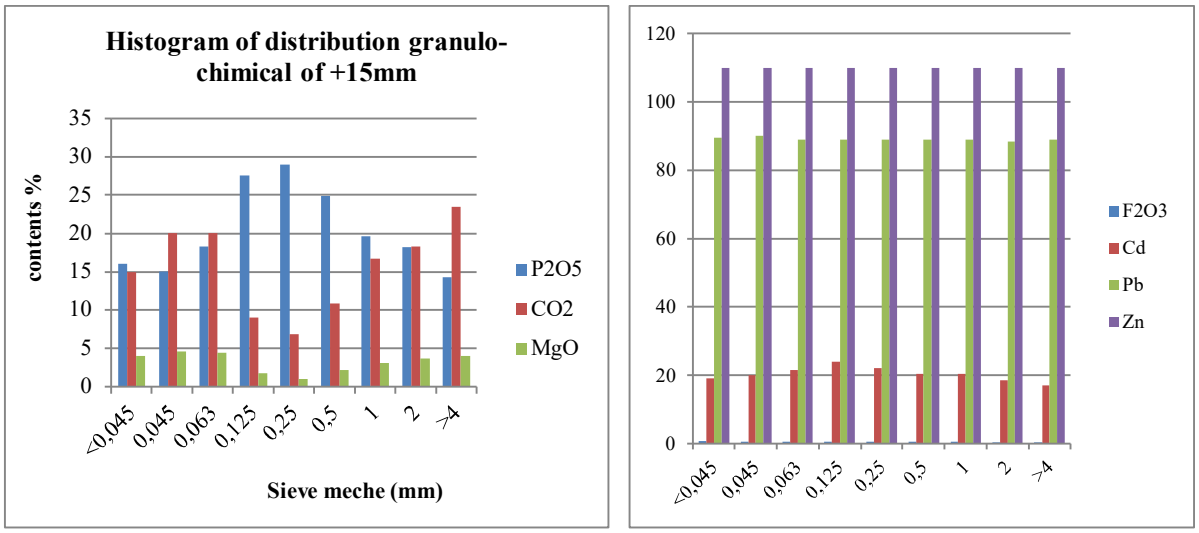
grinding circuit to obtain a suitable particle size. This operation would establish a closed-loop system, reducing material losses and improving overall recovery.

Heavy metal levels (Pb, Zn, Cd, Fe_2O_3) show relative stability for lead and zinc, but marked fluctuations for cadmium and iron oxide (Figure 5). The presence of these elements in the waste

poses a potential risk of soil and water contamination. Regular monitoring and the adoption of appropriate treatment processes are necessary to limit their environmental and health impact [3].

Table 2. Granulo-chemical Analysis Results for +15mm Wastes

Rejects +15 (mm)	Yield Points (%)	P_2O_5 (%)	CO_2 (%)	MgO (%)	CaO (%)	K_2O (%)	Na_2O (%)	F_2O_3 (%)	Cd Ppm	Pb Ppm	Zn Ppm
>4	20.98	14.30	23.42	3.98	23.59	0.006	0.69	0.46	17	89	110
-4 +2	12.36	18.20	18.27	3.65	30.03	0.012	0.86	0.49	18.5	88.5	110
-2 +1	5.65	19.6	16.73	3.15	32.34	0.012	0.74	0.57	20.5	89	110
-1 +0.5	5.83	24.84	10.87	2.16	40.98	0.012	0.81	0.53	20.5	89	110
-0.5 +0.25	22.44	28.99	6.86	1.01	47.83	0.006	0.97	0.62	22	89	110
-0.25 +0.125	14.73	27.57	9.03	1.82	45.49	0.006	0.93	0.53	24	89	110
-0.125 +0.063	8.24	18.27	20.08	4.48	30.14	0.012	0.74	0.55	21.5	89	110
-0.063 +0.045	1.70	15.08	20.08	4.64	24.88	0.018	0.67	0.67	20	90	110
<0.045	8.03	16.07	14.95	3.98	26.51	0.024	0.64	0.79	19	89.5	110



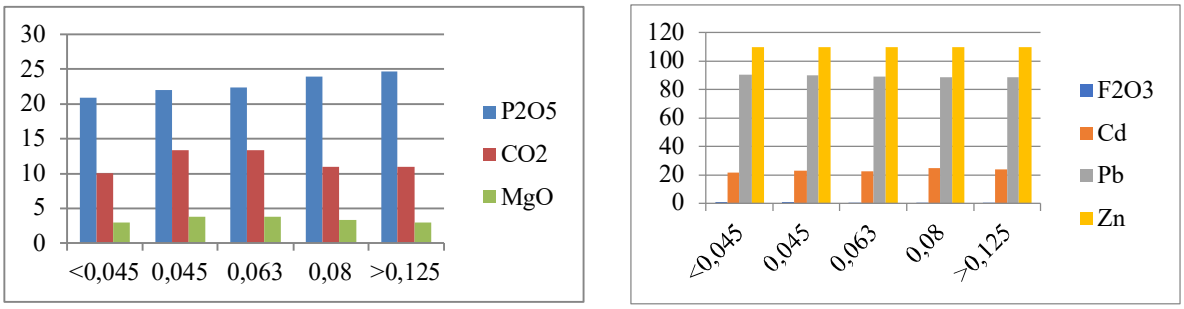
(a) P_2O_5, CO_2, and MgO levels (b) Heavy metal levels

Figure 4. Histogram of P_2O_5, CO_2, MgO and heavy metal Contents (Rejects +15mm)

Table 3. Results of granulochemical analysis of fines (TSV)

FineTSV(µm)	Yield Points (%)	P_2O_5 (%)	CO_2 (%)	MgO (%)	CaO (%)	K_2O (%)	Na_2O (%)	F_2O_3 (%)	Cd Ppm	Pb Ppm	Zn Ppm
>125	39.05	24.67	11.04	2.98	40.70	0.018	0.38	0.55	13.5	89	110
-125 +80	10.70	24.00	11.04	3.32	39.06	0.012	0.81	0.53	24.5	89	110
-80 +63	9.95	22.42	13.38	3.81	36.99	0.012	0.77	0.56	22.5	89.3	110
-63 +45	13.21	21.99	13.38	3.81	36.28	0.012	0.74	0.65	23	90	110
<0.045	27.07	20.83	10.04	34.36	26.51	0.018	0.72	0.81	21.5	90.3	110

The granulo-chemical analyses of the ventilated turbo separator discharge (TSV fines), supported by the histogram (Fig. 5), reveal significant recovery potential. The particle size fractions have P_2O_5 contents ranging from 20.83% to 24.67%, all above the industrial threshold of 15%. The MgO content reaches a minimum of 2.98%, while CO_2 can reach 10.04%, confirming the importance of this parameter for concentrate quality. The CaO content decreases slightly with particle fineness, while heavy metal concentrations remain generally stable. These results indicate that the treatment of TSV fines is technologically feasible. Trace element analysis shows that Zn and Pb have high and relatively constant concentrations in all fractions. Cd varies slightly, with a maximum observed in the 0.08 mm fraction. The Fe_2O_3 content remains very low. Figure 5 illustrates a homogeneous distribution of heavy metals, without marked particle size selectivity.



(a) P₂O₅, CO₂, and MgO levels (b) Heavy metal levels

Figure 5. Histogram of P_2O_5, CO_2, MgO and heavy metal Contents (TSV fines)

7.3. Mineralogical Characterization

7.3.1. SEM/EDS Analysis

Morphological and elemental analyses performed by SEM/EDS on the +15 mm rejects and the fine TSV particles, for the particle size fractions (-500 + 250 µm) and (-63 + 45 µm), reveal a heterogeneous and complex structure. The variability in particle size and texture illustrates the composite nature of the rejects. Bright areas correspond to increased phosphate concentrations, while dark grains reflect the presence of silicates and clays. This heterogeneous distribution confirms that the rejects are not homogeneous and require appropriate recovery treatment.

The presence of angular particles indicates mechanical fragmentation related to the extraction and grinding processes, which increases the specific surface area of the grains. This characteristic can have a dual effect: on the one hand, it promotes the accessibility of reagents during flotation processes; on the other, it increases thermal reactivity during calcination.

-EDS spectra obtained from the phosphate-rich zones confirmed the presence of characteristic elements such as calcium, magnesium, aluminum, carbon, and oxygen. This composition is consistent with the coexistence of phosphate phases (carbonate fluorapatite) and carbonate or aluminosilicate gangue minerals. The uneven distribution of these elements suggests mineralogical segregation, which explains the difficulty of directly obtaining a high-quality phosphate concentrate from raw tailings.

SEM/ED

- Heterogeneous morphology (bright areas = phosphate; dark areas = silicates/clays)

The results of this SEM/EDS analysis are presented in Figure 6.

- Angular particles → mechanical grinding → reactive surface

- Elemental composition: Ca, Mg, Al, C, O → phosphate and carbonate phases

These results therefore highlight that tailing offer potential for P_2O_5 recovery, but require a specific recovery process (flotation).

or calcination) to effectively separate the phosphate phases from the waste phases and improve the quality of the concentrate.

7.3.2. X-ray Diffraction (XRD) Analysis

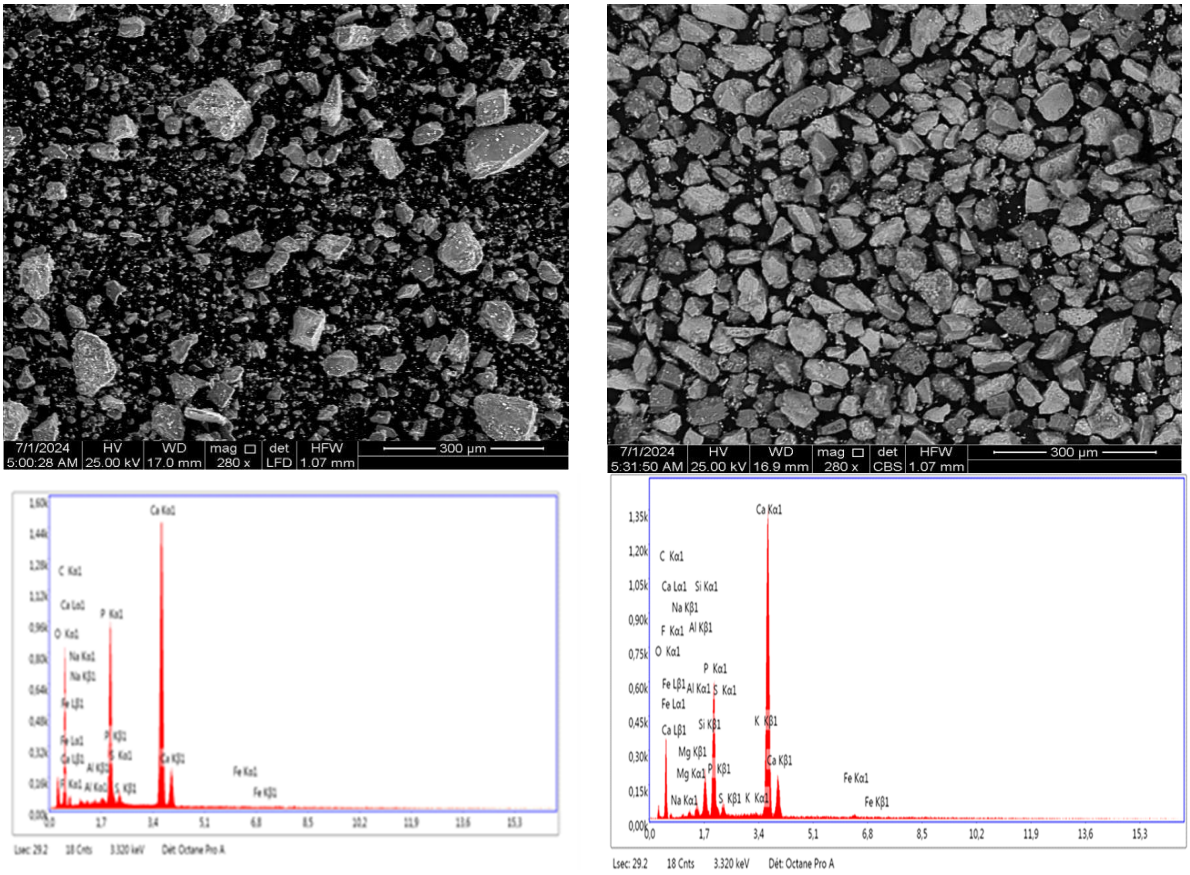
The diffractograms obtained for the +15 mm rejects and the TSV fines (Figure 7) highlight a mineralogical composition dominated by dolomite and hydroxyapatite, constituting the main matrix of the phosphorite grains. The presence of secondary phases such as gypsum, coesite, and hanksite was also detected (Table 4). The dominant peaks at 31.04° 2θ (d = 2.881 Å) for the +15 mm rejects and 30.91° 2θ (d = 2.893 Å) for the TSV fines confirm the coexistence of dolomite and hydroxyapatite in crystalline form.

Beyond identification, the XRD analysis highlights two key points. First, the high proportion of dolomite reveals a significant carbonate content, constituting a limiting factor for direct enrichment of the ore. This justifies the use of thermal treatment (calcination) to promote decarbonation and improve the P_2O_5 concentration. Furthermore, the marked presence of hydroxyapatite, a phosphate mineral of industrial interest, confirms the potential for phosphate recovery by flotation.

Thus, the relative intensity of the peaks related to dolomite and hydroxyapatite highlights the mineralogical heterogeneity of the waste and explains the need for a combination of processes (calcination to remove carbonates and flotation to concentrate the hydroxyapatite). This dual approach is essential to transform the waste into a valuable resource that meets industrial standards.

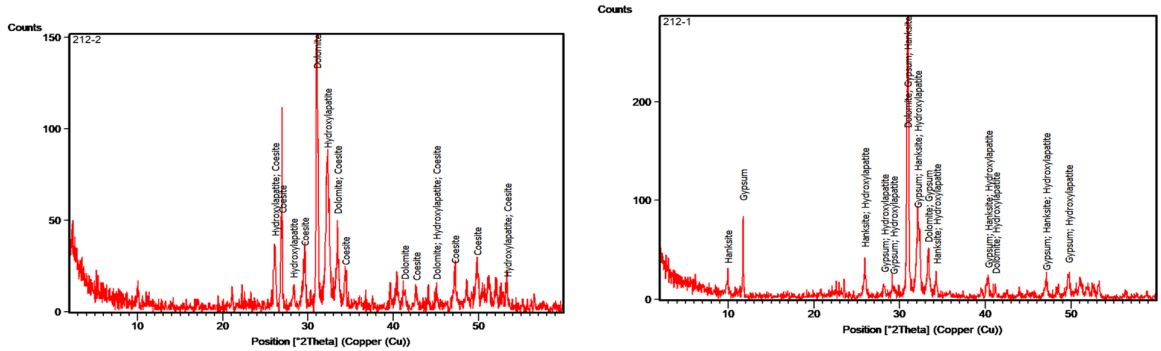
DRX

- Phases dominantes : Dolomite + Hydroxyapatite
- Phases secondaires : Gypse, Coésite, Hanksite
- Photos dominantes 2θ confirmant dolomite / hydroxyapatite



(a) **(b)**

Figure 6. SEM/EDS of the reject samples: (a– rejects +15 mm; b– fine TSV)



(a) **(b)**

Figure 7. XRD analyzes ((a) – rejects +15 mm; (b) – fine TSV)

Table 4. Chemical formula of the minerals studied

Name	Formule chimique
Dolomite	$(CaMg(CO_3)_2)$
Hydroxyapatite	$(Ca_{10}(PO_4)_6(OH)_2)$
Gypse	$CaSO_42H_2O$
Coésite	(SiO_2)
Hanksite	$(K_2Na_{44}(CO_3)_4(SO_4)_{18}O_{84}Cl_2)$

The morphological heterogeneity revealed by the SEM, with the coexistence of phosphate-enriched particles and others composed of silicates and clays, was confirmed by the elemental composition obtained by EDS. Similarly, the XRD diffractograms revealed a matrix dominated by dolomite and hydroxyapatite, accompanied by secondary phases (gypsum, coesite, hanksite). The close association of phosphate and carbonate phases explains the difficulties of direct enrichment of the tailings.

The convergence of the SEM/EDS and XRD results justifies the experimental strategy adopted in this study and confirms the potential for recovering the dry tailings from Djebel Onk.

7.4. Results of chemical analyses of calcined waste.

Results of chemical analyses of calcined waste at different temperatures are presented in Table 05-06.

Table 5. Chemical analyses of calcined waste (15 min)

Temperature C°	Rejects +15 mm calcined at 15 min						
	P_2O_5 (%)	MgO (%)	CO_2 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Cd (ppm)
700	21.79	3.79	13.81	36	0.76	0.012	16
850	25.15	4.21	2.69	41.49	0.84	0.012	18.50
1000	27.28	4.23	1.01	45.01	0.8	0.018	19.50
Temperature C°	Fraction (-0.5+0.25 mm) calcined at 15 min						
	P_2O_5 (%)	MgO (%)	CO_2 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Cd (ppm)
700	32.52	0.88	5.05	53.65	1.01	0.012	18.50
850	32.29	1.1	1.18	53.27	1.03	0.006	20
1000	32.83	1.13	0.51	54.16	1.07	0.018	16.50
Temperature C°	Fine TSVµm calcined at 15 min						
	P_2O_5 (%)	MgO (%)	CO_2 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Cd (ppm)
700	24.79	4.03	8.42	40.90	0.76	0.012	21.00
850	27.02	4.16	2.02	44.5	0.65	0.012	21.00
1000	28.03	4.25	1.68	46.24	0.9	0.03	21.00

Table 6. Chemical analyses of calcined waste (30 min)

Temperature C°	Rejects +15 mm calcined at 30 min						
	P_2O_5 (%)	MgO (%)	CO_2 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Cd (ppm)
700	22	3.64	14.15	36.3	0.76	0.006	18
850	25.25	4.31	1.68	41.66	0.84	0.012	18.50
1000	27.78	4.45	0.51	45.83	0.85	0.006	20
Temperature C°	Fraction (-0.5+0.25 mm) calcined at 30 min						
	P_2O_5 (%)	MgO (%)	CO_2 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Cd (ppm)
700	31.5	0.84	5.05	52	1.02	0.006	18.50
850	32.28	1.1	1.18	53.26	1.04	0.012	19
1000	33.51	1.13	0.34	55.29	1.03	0.018	16
Temperature C°	Fine TSVµm calcined at 30 min						
	P_2O_5 (%)	MgO (%)	CO_2 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Cd (ppm)
700	30.02	3.88	6.74	49.53	0.75	0.006	20.00
850	27.04	4.33	1.35	44.6	0.66	0.006	21.50
1000	28.31	4.38	1.60	46.71	0.93	0.03	21.50

Calcination tests were carried out on the three studied fractions (+15 mm rejects, (-0.5 + 0.25 mm) fraction, and TSV fines) at 700, 850, and 1000 °C for durations of 15 and 30 minutes (Tables 5 and 6).

For 15-minute duration, increasing the temperature resulted in:

A significant decrease in CO_2, indicating progressive decarbonation. In the +15 mm rejects, CO_2 dropped from 13.81 % to 1.01 % between 700 and 1000 °C.

An increase in CaO content, consistent with the decomposition of calcium carbonates ($CaCO_3 \rightarrow CaO + CO_2$).

An enrichment in P_2O_5, reaching 27.28 % for +15 mm rejects, 32.83 % for the (-0.5 + 0.25 mm) fraction, and 28.03 % for TSV fines.

A moderate increase in MgO, particularly in the (-0.5 + 0.25 mm) fraction, where it reached 1.13 %.

For 30-minute duration, the same trends were more pronounced:

CO_2 content dropped to 0.51 %, 0.34 %, and 1.60 % for the three fractions at 1000 °C, indicating almost complete decarbonation.

CaO content reached its highest values, exceeding 55 % in the (-0.5 + 0.25 mm) fraction.

An enrichment in P_2O_5, reaching 27.78 % for +15 mm rejects, 33.51 % for the (-0.5 + 0.25 mm) fraction, and 28.31 % for TSV fines.

The CaO/P_2O_5 ratio stabilized around 1.64, confirming a favorable phosphate-to-carbonate ratio.

These results confirm the thermal decomposition of calcite and dolomite according to the following reactions:

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2$$

The contents of Na_2O, K_2O, and Cd remained low and varied only slightly throughout the treatment. Overall, the results highlight the efficiency of thermal treatment at 1000 °C for 30 minutes in concentrating P_2O_5 and significantly reducing CO_2, thereby improving the quality of the phosphate concentrate**.**

7.5. The direct flotation results.

The direct flotation results of the +15mm rejects, fraction (-0.5+0.25mm) and TSV fines are presented in Table 07.

Table 7. Chemical flotation analyses

Fractions	P_2O_5 (%)	MgO (%)	CO_2 %	CaO (%)	Na_2O (%)	K_2O (%)	F_2O_3 (%)	Cd (ppm)	Pb (ppm)	$\frac{CaO}{P_2O_5}$	$\frac{(MgO+Fe2O3)}{P_2O_5}$
Rejects+15 (mm)	30.42	0.70	5.92	50.19	1.18	0.02	0.34	20	0.00	1,65	0,034
-0,5+0,25 (mm)	29.56	0.93	6.00	48.77	1.08	0.02	0.32	10	0.00	1,65	0,042
Fine TSV (µm)	29.12	1.41	6.65	48.05	1.28	0.01	0.32	30	0.00	1,65	0,059

Direct flotation tests were performed on the three fractions (+15 mm rejects, (-0.5 + 0.25 mm) fraction, and TSV fines) using oleic acid ($C_{18}H_{34}O_2$) as a collector and phosphoric acid (H_3PO_4) as a depressant.

The results show a significant increase in P_2O_5 content in all fractions after flotation (Table 5). The obtained concentrates contain:

- 30.42 % for +15 mm rejects,
- 29.56 % for the (-0.5 + 0.25 mm) fraction,
- 29.12 % for TSV fines.

These values confirm the efficiency of the flotation process for phosphate enrichment.

The MgO content is below 1 % for the first two fractions (0.70 % and 0.93 % respectively), which meets industrial specifications. TSV fines, however, show a slightly higher MgO content (1.41 %), indicating a higher contamination with magnesium carbonates.

Flotation results also reveal:

A CaO/P_2O_5 ratio of about 1.65, confirming the carbonate nature of the ore and its suitability for industrial processing.

A low $(MgO + Fe_2O_3)/P_2O_5$ ratio for the +15 mm rejects (0.034) compared to TSV fines (0.059), highlighting the better quality of the concentrate from coarser fractions [6, 12].

Alkali contents remain very low ($Na_2O \approx 1.1$ %, $K_2O < 0.02$ %), indicating limited presence of aluminosilicate minerals. Similarly, Fe_2O_3 content remains low (0.32–0.34 %), which is beneficial for producing high-quality phosphate fertilizers.

Regarding heavy metals, lead (Pb) is completely absent, while cadmium (Cd) shows significant variability (10–30 ppm), with higher concentrations in TSV fines. This result is critical given the

European limit for fertilizers (≈ 20 mg Cd/kg P_2O_5) [14] and highlights the need for additional treatment to reduce Cd content in this fraction.

Calcination, although effective in increasing P_2O_5 content and reducing CO_2, has a high energy cost that limits its large-scale industrial application. In contrast, direct flotation, which is less expensive and more easily integrated into existing circuits, appears more suitable for industrial deployment. A sequential combination of the two processes could be a viable option, subject to a detailed technical and economic analysis.

The comparative evaluation of calcination and flotation highlights differences in their industrial applicability. Calcination at 1000 °C significantly increases P_2O_5 content (up to 33.5 %) and eliminates almost all CO_2, but its high energy demand and the need for specialized furnaces raise concerns about large-scale feasibility. Optimization of energy consumption, such as continuous kilns or heat recovery systems, would be required to make this process economically viable.

In contrast, direct flotation appears more cost-effective and easier to integrate into existing beneficiation circuits. The reagents used (oleic and phosphoric acids) are relatively affordable and well established in phosphate processing, although operational adjustments are necessary to reduce reagent consumption and improve selectivity.

Overall, calcination offers high technical efficiency but at a high energy cost, while flotation provides a more economical and scalable alternative. A sequential combination of both processes may represent a promising pathway, provided that further pilot-scale and techno-economic studies are conducted.

8. Conclusions

- The dry tailings of Djebel Onk contain 21–23 % P_2O_5, comparable to the raw ore, which justifies their recovery.
- The (-0.5 + 0.25 mm) size fraction is the richest, with 28.99 % P_2O_5, confirming the potential for targeted recovery.
- XRD analysis revealed a composition dominated by dolomite and hydroxyapatite, with secondary phases (gypsum, coesite, hanksite), highlighting the need for a combined treatment.
- Calcination at 1000 °C for 30 minutes produces concentrates with up to 33.5 % P_2O_5 and significant CO_2 reduction, but it involves high energy consumption.
- Direct flotation yields concentrates of about 30 % P_2O_5 with MgO < 1 %, meeting industrial specifications while being a more economical option.
- These results confirm that dry tailings can be effectively valorized, contributing to the national economy and reducing environmental impacts.
- Further studies are needed to assess the techno-economic feasibility and optimize the processes at pilot scale.

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کلمات کلیدی

ضایعات معدن فسفات
کلسیناسیون
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جبل اونک

چکیده

استخراج فسفات در جبل اونک (تبسه، الجزایر) حجم زیادی از زباله‌های جامد تولید می‌کند که زمین را اشغال می‌کنند، گرد و غبار آزاد می‌کنند و محیط‌های اطراف را آلوده می‌کنند. هدف این مطالعه، توصیف و ارزیابی دو نوع باطله خشک، یعنی ضایعات غربالگری +۱۵ میلی‌متری و ذرات ریز حاصل از جداسازی پنوماتیک (TSV)، به منظور کاهش تأثیر زیست‌محیطی آنها و بازیابی فسفات باقیمانده است. نمونه‌ها با استفاده از توزیع اندازه ذرات، طیف‌سنجی جذب اتمی (AAS)، پراش اشعه ایکس (XRD) و میکروسکوپ الکترونی روبشی همراه با طیف‌سنجی پراکندگی انرژی (SEM/EDS) تجزیه و تحلیل شدند. آزمایش‌های تصفیه شامل کلسیناسیون (کوره آزمایشگاهی، ۷۰۰-۱۰۰۰ درجه سانتیگراد، ۱۵-۳۰ دقیقه) و فلوتاسیون مستقیم (سلول نوع دنور، با اسید اولئیک و اسید فسفریک به عنوان معرف) بود. نتایج نشان می‌دهد که ضایعات +۱۵ میلی‌متری و ذرات ریز TSV به ترتیب حاوی ٪۲۱.۴۲ و ٪۲۳ P_2O_5 هستند، در حالی که غنی‌ترین بخش (-۰.۵ + ۰.۲۵ میلی‌متر) به ٪۲۸.۹۹ P_2O_5 با ٪۱.۰۱ MgO می‌رسد. کلسیناسیون در دمای ۱۰۰۰ درجه سانتیگراد به مدت ۳۰ دقیقه، کنسانتره‌هایی با ٪۳۳.۵۱ P_2O_5 و حذف تقریباً کامل CO_2 تولید کرد، در حالی که فلوتاسیون مستقیم، کنسانتره‌هایی با تقریباً ٪۳۰ P_2O_5 با MgO کمتر از ٪۱ تولید کرد. نوآوری این کار در کاربرد ترکیبی کلسیناسیون و فلوتاسیون نهفته است که مکمل بودن آنها را برای بازیابی کارآمد فسفات از باطله‌های خشک نشان می‌دهد. این نتایج، پتانسیل ارزش‌گذاری فسفات را در عین کاهش اثرات زیست‌محیطی و حمایت از شیوه‌های معدنکاری پایدارتر تأیید می‌کند.

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